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Comparative Evaluation of Clothing Thermal Insulation Measured on a Thermal Manikin and on Volunteers

Abstract
This paper analyses the results of comparative clothing thermal insulation measurements determined in tests on volunteers and on a thermal manikin under specified conditions, i.e. a standing man and a standing manikin in a climatic chamber under wind-free conditions. The tests were performed with three ensembles of disposable medical clothing. In tests with a thermal manikin, the heat balance was determined and the temperature and heat losses on the manikin's surface were measured, whereas in tests with volunteers, calculations were made for dry heat losses under the conditions of heat comfort. Clothing thermal insulation values obtained in tests on a manikin and on human subjects were then compared. The results showed the following: 1) thermal insulation of clothing ensembles determined on human subjects was 13% higher than that measured on the manikin; 2) the measurements taken on the manikin were considerably more accurate than those taken on tests with volunteers (manikin's error 2%, subjects' error 12-18%).

Key words: *thermal insulation, heat balance, thermal manikin, medical protective clothing.*

Introduction

Numerous models and indices for evaluating comfort and heat stress [1 - 3] require the thermal insulation of the clothing worn in specific situations to be determined. In optimal conditions, clothing thermal insulation should be determined under real conditions, directly at the workplace. However, in reality measurements are carried out in laboratories during direct tests performed on volunteers or, more frequently, on thermal manikins [4 - 7].

Contemporary research projects aim at extending databases of clothing insulation values by making use of previous results, and they seek to identify other factors influencing clothing insulation [8. 9]. Initially, many authors attempted to standardise the procedure for measuring the protective clothing's thermal insulation by conducting comparative studies on the methods used to determine clothing insulation (i.e. tests on a thermal manikin and on human subjects) under various conditions, i.e. non-wind/standing and wind/moving, as have been conducted in many studies so far [8,10 - 17]. The primary goal of such an approach was to elaborate a coherent ergonomic procedure for evaluating the characteristics of protective clothing thermal [18 - 20]. The present paper also deals with the above-mentioned subject, i.e. analysing selected elements of the clothing insulation measurement procedure with a view to fully understanding and describing all the phenomena connected with the thermal characteristics of protective clothing measurements.

Objective of the study

The main goal of this study was to compare the accuracy of thermal insulation measurements on a thermal manikin and on human subjects wearing various ensembles of medical protective clothing. Furthermore, we intended to acquaint clothes designers and textile producers with the apparatus and basic calculation methodology for measuring clothing thermal insulation in the climatic chamber, on the thermal manikin and in tests on human subjects. Not only does their application enable the assessment of heat insulation of ready-made clothing ensembles, but it is also useful for designing new, more competitive solutions for protective clothing, or other applications such as sleeping bags.

Material and methods

Testing ensembles

Three clothing ensembles were selected for the purpose of this study (Figure 1). They represented typical disposable medical clothing manufactured according to the requirements of standards EN ISO 9001:2001 [22], EN13795-2:2004 [32] and EN13795-3:2004 [35].

Ensemble A – shoes, socks; underwear: underpants and eagle scrub (cotton); surgical ensembles (cotton-like unwoven with hydrophilic viscose fibre, surface mass sq = (65 ± 7) g/m^2, good air and water vapour permeation).

Ensemble B – Ensemble A plus operative apron (two-layer, foiled, sanitary unwoven, polypropylene fibre and polypropylene foil, surface mass sq = (45 ± 2) g/m^2, all liquid-proof).

Ensemble C – Ensemble A plus surgical apron F-1 (thermoplastic, sanitary, two-layer unwoven, polypropylene fibre and hydrophilic viscose, surface mass sq = (35 ± 2) g/m^2, good air permeation).

Measurements from these ensembles were made in a climatic chamber on tests with a thermal manikin and with volunteers.

Climatic chamber

All the experiments on a thermal manikin and with human subjects took place in a climatic chamber, boasting the following parameters:
- temperature range: - 40 °C to +70 °C;
- humidity range: 20% to 90% r.h;
- air velocity range: 0.1 to 3 m/s.

***Figure 1.** Three ensembles of medical disposable clothing.*

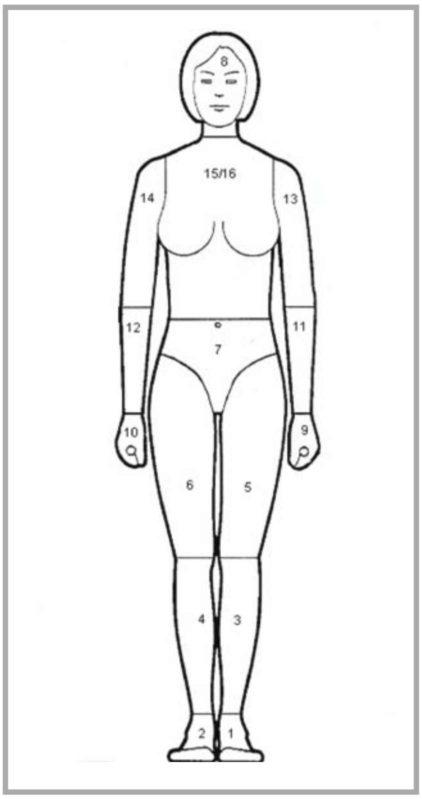

Figure 2. *Sections of thermal manikin (1, 2 – l., r. foot, 3,4 – l., r. leg, 5, 6 – l.,r. thigh, 7 – pelis, 8 – head, 9,10 – l., r. hand, 11, 12 – l., r., forearm, 13, 14 – l., r. upper arm, 15 – chest, 16 – back).*

All tests were conducted under the same conditions; the air temperature (T_a) and the average radiation temperature ($\overline{T}_r$) were controlled by the climatic chamber to an accuracy of 0.1°C. The operative temperature (T_o), i.e. the temperature of a uniform environment that physically and mathematically represents the actual environment, was calculated according to EN ISO 7726:2001 [24]:

$$T_o = \frac{h_c \cdot T_a + h_r \cdot \overline{T}_r}{h_c + h_r}, \qquad (1)$$

where:
h_r - the radiative heat transfer coefficient, (determined from equation 12);
h_c - the convective heat transfer coefficient, (determined from equation 13).

Thermal manikin

The thermal insulation of the ensembles was determined on a thermal standing stationary manikin type TM 3.2/R110, named 'Diana', designed by PT-Teknik, Denmark, and manufactured by the Central Institute for Labour Protection – of the National Research Institute. This is a human body phantom which reflects convective, radiative and conductive heat losses from the manikin's whole surface, either in all directions or from a defined, local surface area. The manikin is made of 16 electrically independent and individually regulated heating segments (Figure 2) with the temperature-sensing elements (nickel wires) distributed all over them. On the basis of measurements of the wires' resistance, the manikin software (MANIKIN 3.x) gives information on the manikin's surface temperature and heat losses for each individual segment, as well as for the segments' average values.

The measurements are taken in accordance with EN ISO 15831:2004 standard [30].

Volunteers

Seven physically sound young men took part in the experiments (Table 1). Prior to the test, they all underwent initial medical examinations in order to exclude any contraindications for tests in the climatic chamber. The physical characteristics of the subjects are presented in Table 1.

Table 1. *Physical characteristics of the subjects. *A_{Du} Body area by Hardy and DuBois.*

Subject	Weight, kg	Height, m	A_{Du}*, m^2	Age, years
AS	70	1.72	1.82	23
JT	65	1.79	1.82	27
TT	71	1.72	1.83	29
PR	67	1.73	1.79	23
KK	77	1.74	1.91	23
AK	81	1.79	1.99	26
ML	80	1.77	1.97	22
Mean	**73.0**	**1.75**	**1.87**	**25**

Experimental procedure

Manikin tests

To determine effective clothing insulation (I_{cle}), it was necessary to calculate the total insulation (I_T) and the insulation of the air layer at the manikin's surface (I_a). Tests were carried out on a standing manikin, with the temperature for each of its 16 segments set at 34 °C and the ambient parameters in the climatic chamber set as presented in Table 2.

Two series of the experiment were carried out:
Series I – on a naked manikin, in which the insulation of air layer (I_a) was determined for different ambient temperatures in order to calculate the various values of dry heat losses (H). Nine experimental sessions were conducted; each test was repeated three times and each lasted about 4 hours.

Series II – on a dressed manikin, in which the total thermal insulation (I_T) was determined for all ensembles (A, B, C). Twelve experimental sessions were carried out; each test was repeated four times and each lasted about 4 hours.

All the measurements were taken at 1-second intervals, and a 1-minute average value was subsequently calculated and recorded. The results were constantly displayed to help to evaluate the state of thermal balance.

Tests with human subjects

Tests with volunteers were carried out with the same ensembles (A, B, C), and under exactly the same conditions in the climatic chamber as with the thermal manikin (standing posture at rest, practically the same thermal exposure).

The following parameters were measured or calculated:
- total thermal insulation (I_{Thuman}) and the insulation of air layer (I_{ahuman}) (the 'human' index indicates insulation calculated on the basis of tests with volunteers),
- the metabolic rate (M), which was determined with an MMC Sensor Medics 2900 on the basis of the volume of absorbed oxygen measurements and carbon dioxide emissions, according to standard EN ISO 8996:2005 [34].
- body and skin temperatures, (T_{re} and T_{sk}) which were taken with an accuracy up to 0.15 °C by means of a standard thermocouple with the aid of a 15 channel device manufactured by Ellab,
- weighted average skin temperature, which was calculated on the basis of the measurements taken at 8 points: forehead, right scapula, left upper chest, right arm in the upper location, left arm in the lower location, left hand, right anterior thigh and left calf [23],

Table 2. *Mean values and standard deviations for air temperature (T_a), globular thermometer temperature (T_g), operative temperature (T_o), manikin surface temperature (T_{cms}) and manikin heat losses (H) recorded during the experiment.*

Clothing ensemble	Experimental conditions (manikin dressed)			
	T_a, °C	T_g, °C	T_o, °C	T_{cms}, °C
A	23.6 ± 0.1	23.6 ± 0.1	23.6 ± 0.1	33.7 ± 0.1
B	23.4 ± 0.1	23.4 ± 0.1	23.4 ± 0.1	33.8 ± 0.1
C	23.7 ± 0.1	23.5 ± 0.1	23.6 ± 0.1	34.3 ± 0.1

- the heart rate, which was determined by counting ECG waves,
- sweat vaporisation, on the basis of volunteers and their clothing weighting, before and after each session, with accuracy up to ± 5 g. An extra measurement was taken at the 90th minute of the experiment.

The basic and derivative parameters of the microclimate were measured in accordance with standard EN-ISO 7726: 2001 [24]. Measurements and calculations were recorded at five-minute intervals. Each measuring session in the climatic chamber took 120 minutes. A total of 21 experimental sessions were conducted (i.e. each clothing ensemble was tested on seven human subjects).

Calculating clothing thermal insulation

The calculation methodology (I_T) is determined by the type of test performed, i.e. whether it is carried out on a thermal manikin or on human subjects. An obligatory unit of clothing insulation (I_a, I_T) is m^2K/W, although clo is the term commonly used [27]. One clo is defined as the thermal insulation necessary to maintain the thermal balance of a sitting subject in a room with the following ambient parameters: air velocity equal to 0.1 m/s, air and wall temperature at 21 °C and humidity less than 50% r.h. Under these conditions, 1 clo corresponds to the insulation of a clothing ensemble equal to 0.155 m^2K/W.

Effective clothing insulation calculated on a thermal manikin

Effective clothing insulation (in clo units) is calculated on the basis of the difference between total insulation and the insulation of the boundary layer, i.e. the air layer surrounding the manikin, using the equations presented below (2 - 4).

Total insulation (I_T) is the insulation from the surface of the manikin to the environment, including the heat resistance of the boundary air layer (I_a) (2).

$$I_T = \frac{\overline{T}_{cms} - T_o}{H} \quad (2)$$

where:

$\overline{T}_{csm}$ – the average temperature of the manikin surface when dressed, °C;

T_o – the operative temperature (see equation 1)

H – the heat stream power density, W/m^2.

Air insulation at the surface of the manikin (I_a) is obtained from equation (3) presented below:

$$I_a = \frac{\overline{T}_{nms} - T_0}{H} \quad (3)$$

where:

$\overline{T}_{nms}$ is an average temperature of the naked manikin surface (nms = naked manikin surface).

Finally, effective clothing insulation (I_{cle}) can be calculated on the basis of equation (4):

$$I_{cle} = I_T - I_a \quad (4)$$

Clothing insulation calculated on volunteers

Clothing thermal insulation when tested on human subjects is determined on the basis of the thermal balance of the human body equation, whereby dry heat loss (H_{DRY}) from the body surface to the environment, consisting of radiative (R) and convective (C) heat loss, is calculated according to the following equations [5, 8, 25, 26]:

$$H_{DRY} = C + R = \\ = M - W - E_{sk} - E_{res} - C_{es} - S \quad (5)$$

where:

E_{sk} – evaporative heat loss rate, W/m^2

$E_{res} + C_{res}$ – evaporative and convective respiratory heat loss rate, W/m^2

S – body heat storage rate, W/m^2.

Metabolic heat production (M) was measured by the rate of respiratory oxygen consumption and carbon dioxide emission according to the following equation (6):

$$M = \frac{257{,}95 \cdot V_{o2}}{A_{Du}} \quad (6)$$

The external work rate (W) during the experimental conditions (standing, motionless) was zero, whereas evaporative heat loss (E_{sk}) was calculated using the following formula (7):

$$E_{sk} = \frac{3{,}06}{A_{Du}} \cdot 10^{-3}\left(256\overline{T}_{sk} - 3360 - p_a\right) \quad (7)$$

where:

p_a – the water vapour pressure in ambient air, kPa

During respiration, the volunteers lost sensible and latent heat by convection and evaporation. These losses (E_{res} + + C_{res}) were calculated on the basis of metabolism rate measurements using the following equation (8):

$$C_{res} + E_{res} = 0.0014M(34 - T_a) + \\ + 0.0173\, M(5.87 - p_a) \quad (8)$$

where:

p_a – ambient pressure, kPa.

The amount of heat loss from sweat evaporation was calculated on the basis of weight loss in the volunteers [5, 8]. Heat accumulation was calculated on the basis of the rectal temperature change and the weighted average skin temperature [27].

As with the manikin test (described previously), total clothing insulation (I_T) and effective clothing insulation (I_{cle}) were calculated on the basis of the following equations:

$$I_{T(human)} = \frac{\overline{T}_{sk} - T_0}{M - W - E_{sk} - E_{res} - C_{res} - S} \quad (9)$$

$$I_{cle(human)} = I_{T(human)} - I_{a(human)} \quad (10)$$

where:

I_a – air insulation on the body surface of the ‘naked’ volunteer (i.e. dressed only in underpants, socks, shoes) calculated on the basis of given formula (11) [27, 31]:

$$I_{a(human)} = 1/(h_c + h_r) \quad (11)$$

where:

h_c – the convective heat transfer coefficient, $W/(m^2\,K)$,

h_r – the radiative heat transfer coefficient, $W/(m^2\,K)$.

Convective heat transfer coefficient depends on air velocity, which defines the type of the convention:

- for small air flow velocities (V_a < 1 m/s) there is a free convection type, for which:

$$h_c = 3.5 + 5.2 \cdot V_a \quad (12)$$

- for higer velocities (V_a > 1 m/s), the forced convection is as follows:

$$h_c = 8.7 \cdot V_a \quad (13)$$

Radiative heat transfer coefficient is determined from the following equation (14)

$$h_r = \sigma\varepsilon \frac{A_r}{A_{Du}} \frac{\left[\left(\overline{T}_{sk} + 273\right)^4 - \left(t_r + 273\right)^4\right]}{\overline{T}_{sk} - \overline{T}_r} \quad (14)$$

where:

σ - the Stefan-Boltzmann constant, $5.67 \cdot 10^8\ Wm^{-2}k^{-1}$

ε - the average emissivity of clothing or body surface, dimensionless

$\frac{A_r}{A_{Du}}$ - the part of skin area included in radiation heat transfer, dimensionless

Table 3. Mean values and standard deviations for the total (I_T) and effective (I_{cle}) insulation of 3 tested clothing ensembles measured on a standing manikin, with air velocity in the climatic chamber ≤ 0.1 m/s.

Clothing ensemble	H,	I_T,		I_{cle},	
	W/m²	m²K/W	clo	m²K/W	clo
A	49.2 ± 0.4	0.206 ± 0.001	1.33 ± 0.01	0.084 ± 0.001	0.54 ± 0.01
B	47.7 ± 0.4	0.218 ± 0.002	1.40 ± 0.01	0.096 ± 0.002	0.62 ± 0.01
C	39.8 ± 0.2	0.269 ± 0.001	1.74 ± 0.01	0.147 ± 0.001	0.95 ± 0.01

$\overline{T}_{sk}$ - the area-weight average skin temperature, °C

$\overline{T}_r$ - the average radiation temperature, °C.

All measurements and calculations were performed in accordance with standard EN-ISO 9920:2003 [21].

Statistics

In order to compare the influence of particular parameters (T_o, T_{cms}, H, M) on clothing thermal insulation, an analysis of the ANOVA variance test (for many averages) as well as a test for two averages were used. A coefficient of significance α=0.05 was adopted. The calculations were made with the Statgraphics statistics package.

Results

Clothing thermal insulation measured on a thermal manikin

Table 3 shows the results of the calculation of total and effective clothing insulation for selected ensembles obtained in tests on the thermal manikin.

The relative measuring error of total clothing insulation (I_T) defined as a composite value error amounting to about 3%. Its value was influenced by the measurement errors of the following parameters (given together with their percentage share in the total, i.e. a 3% measurement error):

- operative temperature (T_o) – 56%,
- manikin surface temperatures (T_{cms}) – 35%,
- heat losses from the manikin surface (H) – 9%.

In turn, the relative error of the clothing thermal insulation measurements did not exceed 2%. The tests showed that for such a small measurement error (2%), the indispensable number of measurements can be reduced to 3. For the result to be even more accurate (i.e. to within 0.01 clo), the minimum number of measurements should not be smaller than 11 (the estimate based on the average variance of the results).

The differences between the mean values of the ensembles insulation were statistically insignificant (ANOVA test, F = 1000).

For the measured values $(\overline{T}_{nms} - T_0)$ and the H air-layer, the insulation at the surface of the manikin was 0.78 clo (Figures 3 and 4).

Figures 3 & 4. Interdependence between the air thermal resistance at the manikin surface (I_a) and (T_{nms}-T_o) or H recorded in the experiments with the 'naked' manikin. The broken lines indicate 95% confidence intervals for the mean values and the measurement results.

Clothing thermal insulation measured on volunteers

Tables 4 and 5 present the parameters of thermal balance (Table 4) as well as the thermal insulation calculated for different ensembles (Table 5).

The relative measuring error of clothing insulation (I_T) defined as a composite value error amounted to about 6%.

Its value was influenced by the measurement errors of the following parameters (given together with their percentage share in the total, i.e. a 6% measurement error):

- metabolism (M) – 52%,
- skin temperature (T_{sk}) – 24%,
- operative temperature (T_o) – 16%.

In turn, the relative error of the clothing thermal insulation measurements fluctuated between 12% and 18%. The tests showed that in order for the error to be comparable to the one obtained in tests on the thermal manikin (i.e. 2%), the number of measurements on volunteers should amount to at least 600. Reducing the number of measurements to 8 results in the increase of the measurement error to 20% (in the material under discussion, with 7 volunteers participating in the tests, the error remained within the 12 - 18% bracket). The differences between the mean values of the ensembles were statistically insignificant.

Comparing the calculations of human/manikin clothing's thermal insulation

Figures 5 and 6 present the comparison of the calculations of clothing thermal insulation carried out on volunteers and on a thermal manikin.

The mean values and standard deviation for the total (I_T and $I_{T(human)}$) and effective (I_{cle} and $I_{cle(human)}$) clothing thermal insulation were calculated on the basis of all experimental sessions. The differences between the mean clothing thermal insulation determined on volunteers and on the thermal manikin for ensembles A and B were statistically significant (coefficient of significance = 0.02-0.03). The difference was about 13%; higher insulation was obtained when measured directly on human subjects than on the manikin. The air-layer insulation at the 'naked' volunteer's skin surface (the subject devoid of clothing) was 0.78 clo.

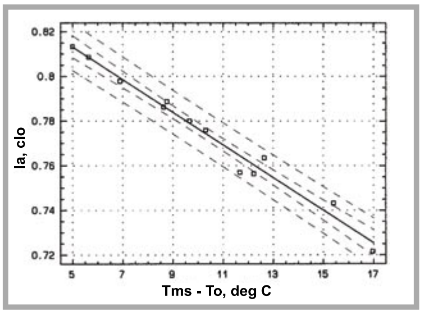

Figure 3. Interdependence between the air thermal resistance at the manikin surface (I_a) and (T_{nms}-T_o) recorded in the experiments with the "naked" manikin. The broken lines indicate 95% confidence intervals for the mean values and the measurement results.

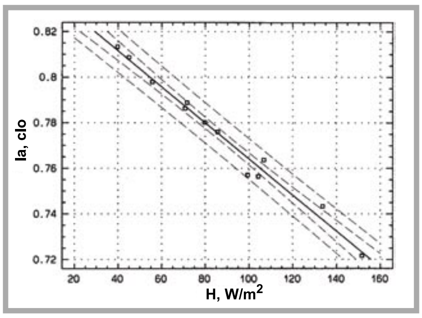

Figure 4. Interdependence between the air thermal resistance at the manikin surface (I_a) and H recorded in the experiments with the "naked" manikin. The broken lines indicate 95% confidence intervals for the mean values and the measurement results.

Table 4. Mean values and standard deviations for skin temperature and body (rectal) temperatures (T_{sk}, T_{re}) and the balance elements for balance conditions (final 30 minutes of the experiment) concerning the three ensembles tested.

Parameter (˚C), ()	A	B	C
$\overline{T}_{sk}$, °C	33.1± 0.2	33.0 ± 0.1	33.5 ± 0.2
T_{re}, °C	37.3 ± 0.3	37.3 ± 0.3	37.4 ± 0.3
M, W/m^2	44.0 ± 7.2		
C_{res}, W/m^2	0.7 ± 0.01		
E_{res}, W/m^2	3.5 ± 0.02		
E_{sk}, W/m^2	insignificant		
S, W/m^2	heat loss statistically insignificant (S<1-2% M)		

Table 5. Mean values and standard deviations for the total and effective insulation of the 3 ensembles tested on standing volunteers at rest. Air velocity in the climatic chamber ≤ 0,1 m/s.

Ensemble	$I_{T(human)}$		$I_{cle(human)}$	
	m^{2}K/W	clo	m^{2}K/W	clo
A	0.25 ± 0.03	1.6 ± 0.2	0.13 ± 0.03	0.8 ± 0.2
B	0.25 ± 0.03	1.6 ± 0.2	0.13 ± 0.03	0.8 ± 0.2
C	0.28 ± 0.05	1.8 ± 0.3	0.16 ± 0.05	1.0 ± 0.3

Discussion

As already mentioned in the introductory part of this paper, clothing insulation properties can be evaluated on the thermal manikin or in tests with human subjects. The values of clothing thermal insulation obtained in tests on a human subject and on a thermal manikin are not identical. A comparative analysis carried out by the authors indicated that insulation is higher when measured directly on volunteers than on a thermal manikin (difference of 13%).

Nielsen et al. [6] and Olesen et al. [7] also put forward a higher value of clothing insulation (0.22 clo) when determined on human subjects, whereas Havenith et al. [8] suggested contrary results; manikin data for the conditions "standing/ no wind" was higher by 0.15 clo on average in comparison with the results obtained in similar tests on humans. Similarly, Nishi et al. [27] and Vogt, et al. [5] observed higher clothing insulation when measured on manikins than on volunteers. These differences could be partially accounted for by improper, (too small) clothing fit, which would result in a higher value of clothing insulation for a manikin (by 0.008 clo on average), as in most cases test clothing is fitted for subjects who are taller than manikins [8].

In recent comparative tests with volunteers and manikins which were perfectly selected in terms of size and methodology applied (the direct measurement of dry $(C + R)_{sk}$ heat losses) and uniform conditions of testing (a volunteer/manikin motionless and standing, and no wind in the climatic chamber), the results of insulation measurements on volunteers and manikins were practically the same (difference 0 – 0.7%) [11].

In the present paper, the authors compared clothing insulation determined on a group of seven males with an average height of 175 cm and body area amounting to 1.87 m^2 with the clothing insulation determined on a manikin with a height of 168 cm and body area of 1.6 m^2. Selecting bigger clothing for the subjects and smaller clothing for the manikins reduced the potential influence of improper clothing fit on the clothing insulation. Despite the proper fit of the tested garments, differences were still noted between the thermal insulation values of the thermal manikin and the volunteers. These could be attributable to the following factors:

- differences in the shape of the manikin and the subjects tested influencing the final clothing fit, and consequently the clothing thermal insulation, resulting from differences in heat resistance of the boundary air layer (I_a),
- test duration (120 minutes), the impact of physiological reactions taking place in the volunteers (metabolism, heart rate, sweat vaporisation) and particularly the uncomfortable conditions for humans (motionless/standing position, apparatus for respiratory gases measurements [a mouth mask]), which may if left unattended diminish the accuracy of clothing thermal insulation [8].

Havenith et al. [8] managed to significantly reduce the errors connected with sweat evaporating on clothing thermal insulation by covering their 4 male volunteers with synthetic foil before putting on the ensembles. They assumed the foil temperature to be the skin surface temperature. The formula defining the subject's body temperature (Tc = core temperature) in the experiment was as follows:

$$Tc = (0.9 \times dT_{re}/dt + 0.1 \times dT_{folia}/dt \quad (15)$$

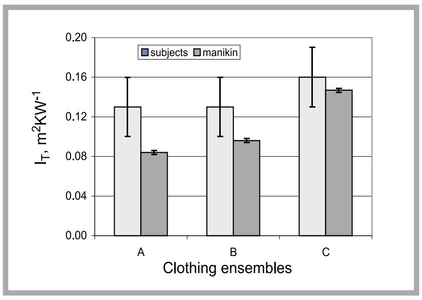

Figure 5. Comparison of total clothing insulation (I_T) in direct tests on volunteers and on a thermal manikin.

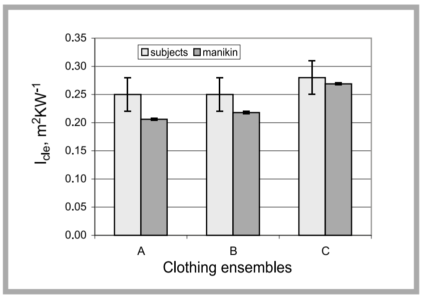

Figure 6. Comparison of effective clothing insulation (I_{cle}) in direct tests on volunteers and on a thermal manikin.

By using foil, the sweating factor was eliminated, and thus conditions for heat exchange became comparable to those between the manikin and the environment.

In our experiments with human subjects, the negative impact of sweat was limited, because the conditions under which the tests were performed corresponded to the conditions of thermal comfort; the PMV (Predicted Mean Vote, an index of thermal comfort) was -0.47. Additionally, heat losses were limited in such conditions (S < 1.5%M) , which resulted in a low body temperature, and consequently in little sweating.

On the other hand, it is important for measurements of skin temperature and dry heat losses to be automatically recorded constantly at minute intervals [11, 12, 19, 28, 29]. However, in reality only a few laboratories are prepared to constantly record weight losses with a level of accuracy of ± 1 - 2 g, irrespective of the dynamic disturbance connected with body movements and to clothing temperatures with an accuracy level of ± 0.05 °C.

Another issue concerns the repeatability of the clothing thermal insulation results which are conditioned by measurement error. In our studies, the relative measuring error estimated in tests on a thermal manikin did not exceed 2%, whereas in tests on volunteers it was several times higher (12%-18%). The findings revealed that in order to achieve as small a measuring error as the one obtained in tests on the thermal manikin, up to 600 tests would have to be performed on human subjects. Individual differences in the subjects' physiological reactions and the magnitude of factors influencing the human thermal balance make it difficult to obtain precise values of thermal insulation measurement. However, tests performed at real workstations with volunteers with properly fitted tested ensembles – that is, considering exact body movements and postures when performing work tasks – provide the most accurate results regarding heat exchange between a human and the environment. However, the limited extent to which test conditions can be matched with the real requirements influences the occurrence of individual differences in subjects' physiological reactions. This in turn entails numerous repetitions of the tests, and as a result, the number of measurements carried out increases costs outlays, and more time is needed to obtain the results.

Hence the idea of testing clothing thermal insulation on the thermal manikin. Not only does it enable time-effective and accurate tests to be carried out, but it also makes recreating measurement conditions possible, as well as to simulate heat exchange at particular segments of the manikin. Still, such a test result is a compromise between simplicity, low costs and a real representation of all the processes influencing heat balance, which is reflected in the clothing thermal insulation value.

Therefore, it is anticipated that new calculation models will improve the level of accuracy with regard to measurements of heat exchange between the human and the environment. The new models are based both on the data obtained from thermal manikin tests and from experiments with the participation of volunteers; that is, the real distribution of temperatures on a human's skin for given testing ensembles. It should also be pointed out that the insulation value is determined by a number of other factors, such as air velocity and body movement, which considerably decrease the thermal insulation of clothing ensembles, particularly in tests on the thermal manikin. For example, clothing ensemble insulation measured on a moving thermal manikin and volunteer and air velocity > 0.1 m/sec. is reduced by 32.6% and 10% respectively, but the eff-ect of this mechanism remains unknown (11).

The tests were conducted on medical protective clothing ensembles which met the requirements of standard EN13795-2: 2004 32.. They consider resistance to microbial penetration, microbial cleanliness, linting, bursting strength, tensile strength and other factors. In the standards for medical protective clothing, not much attention has been paid to the so-called physiological comfort of the user. This fact has already been signalled in the studies published by the institutes carrying out the comprehensive assessment of different properties of protective clothing, including medical ensembles [33].

Conclusions

1. The difference in clothing thermal insulation determined in the climatic chamber on a standing and a motionless thermal manikin and on volunteers, under non-wind conditions, is 13%.
2. Higher insulation is obtained when calculated/measured on volunteers than on a thermal manikin.
3. Clothing thermal insulation measurements carried out on a thermal manikin are several times more accurate than the ones taken on volunteers (an error of 2% on the manikin, 12-18% on the subjects).

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References

1. *EN ISO 7730:1995 Moderate thermal environments: Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.*
2. *EN ISO 7933:2004, Hot environments; analytical determination of thermal stress (Required Sweating), International Standard Organisation, Geneva.*
3. *ISO/TR 11079:1993. Evaluation of cold environments– Determination of required clothing insulation (IREQ).*
4. *McCullough E A, Jones B., W., and Huck P.E. J (1985) A comprehensive database for estimating clothing insulation, ASHRAE Transactions 91(2A), 29-47.*
5. *Vogt J.J., Meyer J P., Candas V, Libert J. P., & Sagot J. C., (1983) Pumping effects on thermal insulation of clothing worn by human subjects. Ergonomics, 26, 10, 963-974.*
6. *Nielsen R, Olesen B.W.,& Fanger P. O., (1985) Effect of physical activity and air velocity on the thermal insulation of clothing, Ergonomics, 28, 1617-1632.*
7. *Olesen B. Sliwinska E. E, Madsen T, and Fanger P. O., (1982) Effect of body posture and activity on the insulation of clothing. Measurement by a movable thermal manikin. ASHRAE Transactions, 32, 791-805.*
8. *Havenith G., Heus R., & Lotens W. A. (1990) Resultant clothing insulation: a function of body movement, posture, wind, clothing fit and ensemble thickness. ERGONOMICS, 33, 1, 67-84.*
9. *Sołtynski K, Konarska M, Pyryt J & Sobolewski A. (1999) Test research of a new generation thermal manikin. Proceedings of the Third International Meeting on Thermal Manikin Testing, 31MM, at the National Institute for Working Life, October 12-13, 1999. Eds: H. O. Nilsson, I. Holmer p. 19-23.*
10. *Afanasieva R.F., (1994) Physiological and hygienic clothing requirements for protection against cold, methods determination of thermal resistance, assessment. In: Holmer I., Eds. Work in cold environments. Invest. Report, 1994:31. 96-103, Sweden.*
11. *Afanasieva R.F., Bessonova N.A., Burmistrova, O.V., Burmistrov V.M., Holmer I., Kuklane K., (2000) Comparative evaluation of the methods for determining thermal insulation of clothing ensemble on a manikin and person. Proceedings of NOKOBETEF 6th and 1st European Conference on Protective Clothing at the National Institute for Working Life., 188-191.*
12. *Nilsson H.O., (1997) Analysis of two methods of calculating the total insulation. In: Thermal Manikin Testing. Proceedings of a European Seminar at the National Institute for Working Life, pp. 17-22.*
13. *Nilsson H.O, Anttonen H., Holmer I., (2000) New algorithms for prediction of wind effects on cold protective clothing. In Kuklane K., Holmer I., editors. Ergonomic of protective clothing. Proceedings of NOKOBETEF 6 and 1st European Conference on protective Clothing (Arbete och Halsa No. 2000:8) Stockholm, Sweden: National Institute of Working Life; 17-20.*
14. *Higenbottam C., Neale M. S. & Witney W. R. (1997) Thermal manikin measurements for human thermoregulatory modelling: the needs and options. In: Proceedings of a European Seminar at the National Institute for Working Life, 6-16.*
15. *Holmer I., (1999) Thermal manikins in research and standards. Proceedings of the Third International Meeting on Thermal Manikin Testing, 31MM, at the National Institute for Working Life, October 12-13, 1999. Eds: H. O. Nilsson, I. Holmer, 1-7.*

16. Parsons K. C., (1988) Protective clothing: heat exchange and physiological objectives. ERGONOMICS, 31, 7, 991-1007.
17. Parsons K.C., Havenith G., Holmer I., Niksson H., Malchaire J., (1999) The effects of wind and human movement on the heat and vapour transfer properties of clothing. Ann. Occup.Hyg., 43, 347-352.
18. Anttonen H., Niskonen J., Meinander H., Bartels V., Kuklane K., Reinerstsen R.E., Varieras S., Sołtyński K., (2004) Thermal manikin measurements – exact or not? International Journal of Occupational Safety and Ergonomics (JOSE) 10, 291- 300.
19. Meinander H., Anttonen H., Bartels V., Holmer I., Reinesrtsen R.E, Sołtyński K., Varieras S., (2003) Thermal insulation measurements of cold protective clothing using thermal manikins. SUBZERO project, final report. Tampere, Finland: Tampere University of Technology; 2003. Report No.4:2003.
20. EN 13921:2005. Personal protective equipment – Ergonomic principles.
21. EN ISO 9920:2003. Ergonomics of the thermal environment – Estimation of the thermal insulation and evaporative resistance of a clothing ensemble. Report International Standard Organisation, Geneva.
22. EN ISO 9001:2001. Quality management systems. Requirements.
23. EN ISO 9886:2004. Ergonomics – Evaluation of thermal strain by physiological measurements. European Committee for Standardisation, Brussels.
24. EN ISO 7726: 2001. Ergonomics of the thermal environment – Instruments for measuring physical quantities.
25. Havenith G., Holmer I., den Hartog E. A. & Parsons K (1999) Clothing evaporative heat resistance-proposal for improved representation in standards and models. Am Occup Hyg, 43: 339-346.
26. Holmer I., Nilsson H., Rissanen S., Hirata K., Smolander J., (1992) Quantification of heat balance during work in three types of asbestos-protective clothing. Int. Arch. Occup. Environ. Health, 64:243-249.
27. Fanger P.O., (1970) Thermal comfort: analysis and applications in environmental engineering (Danish Technical Press, Copenhagen).
28. Nishi Y., Gonzalez R. R., & Gagge A. P., (1975) Direct measurement of clothing heat transfer properties during sensible and insensible heat exchange with thermal environment. ASHRAE Transactions, 81, 183-199.
29. Holmer I., Nilsson H., Havenith G., Parsons K., (1999) Clothing convective heat exchange-proposal for improved prediction in standards and models Ann. Occup. Hyg. 43, 329-337.
30. EN ISO 15831:2004 Clothing - Physiological effects - Measurement of thermal insulation by means of a thermal manikin.
31. ASHRAE, HVAC Fundamentals Handbook, 1997.
32. EN13795-2:2004 Hospital equipment, Surgical equipment, Protective clothing, Gowns (protective), Medical equipment, Cleaning, Cleanliness tests (textiles), Microbiological analysis, Biological analysis and testing, Particulate materials, Performance testing, Water-resist.
33. Bartels V.T., Umbach K.H.: Psychological function and wear comfort of protective clothing with the examples of OR-gowns and fire fighters garments, Proceedings 4. Int. Conference on Safety and Protective Fabrics, Pittsburgh, USA, 2004.
34. EN ISO8996:2004 Ergonomics, Working conditions (physical), Human body, Heat, Classification systems, Metabolism, Human biology, Mathematical calculations, Occupations, Accuracy.
35. EN13795-2:2006 Surgical drapes, gowns and clean air suits, used as medical devices for patients, clinical staff and equipment – Part 3: Performance requirements and performance levels.

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Latest news

*On 22 April 2007, **Bogdan Mac, M.Sc., Eng., the Editor-in-Chief of Fibres & Textiles in Eastern Europe**, was awarded the **Prize of the City of Łódź** by the resolution of the City Council for his outstanding achievements in editing the journal. The ceremony took place at a special session of the Council at the presence of all the six prizewinners, the Presidents of the Council and the City of Łódź on 15 May 2007, the rectors of the universities, academies and other university schools, and the presidents of associations, among other. The official ceremony was followed by a chamber concert and a small reception.*

***Bogdan Mac**, born in Łódź in 1935, attended the State Technical-Industrial High School from 1948 to 1952, and obtained the degree of M.Sc. from the Technical University of Łódź in Electrothermal Engineering in 1959 from. Both before and after studies he worked in industry, and in addition from 1960 at the Technical University. Since 1962 Bogdan Mac has been connected with the Institute of Artificial and Synthetic Fibres, at present the Institute of Biopolymers and Chemical Fibres. He worked as a researcher and department & laboratory manager. During this time he developed constructions of new apparatuses and measurement systems for use in chemical fibre science and industry, as well as new technologies in the field of chemical fibres, especially new kinds of fibres. He is the author and co-author of over twenty patents and also scientific publications. Twice, in 1981 and 1987, years of great economical and political transformation, he was elected president of the Council of the Institute, and until 2000 he was active as a member of the Scientific Board. In 2000 the General Meeting of the Academy of Engineering in Poland elected **Bogdan Mac** as a full member of the Academy, and at present he fulfils the duties of the chancellor of the Łódź region. In 2005 he was awarded honorary membership of the Polish Textile Association, which had already awarded the journal Fibres & Textiles in Eastern Europe with the Golden Order of the Association. The journal was founded in 1992, and since almost the very beginning Bogdan Mac has been active in editing it. As of No. 2 of vol.1, 1993, **Bogdan Mac** has been Editor-in-Chief. His hobby is alpinism (he is an honorary member of the Łódź High Mountaineering Club), skiing and horse riding, as well as photography and amateur painting.*

Editor Bogdan Mac with Prof. Jan Krysiński, roctor of TU Łódź.

*We congratulate **Mr Bogdan Mac** on his outstanding success, and wish him great personal satisfaction in his work, further fruitful creativeness in evolving continuing editorial excellence of the journal and establishing its deserved position among the world's scientific journals devoted to fibres and textiles.*

On behalf of myself, the entire Editorial Committee, all the editors, and the staff of the Institute of Biopolymers and Chemical Fibres

Danuta Ciechańska Ph.D., - Managing Director of the Institute